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Reconstruction of Central European daily weather types back to 1763

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ABSTRACT: Weather type classifications (WTCs) are a simple tool to analyse variations in weather patterns. Long series of WTCs could be used to address decadal changes in weather as a basis for studying changes in variability or extremes or for addressing contributions of sea-surface temperature or external forcings using climate models. However, there is no long series of daily objective weather types (WTs). A new method (Shortest Mahalanobis Distance, SMD) using daily European weather data is developed to reconstruct WTCs back in time. Here the SMD method is applied on the Cluster Analysis of Principal Components (CAP9) classification used by MeteoSwiss. The CAP9 daily WT time series (computed with ERA-40) is used as reference over the 1958–1998 period. Daily data (temperature, mean sea level pressure and pressure tendency) from 13 European stations covering the period 1763–2009 are used for the reconstruction. The reference CAP9 is reduced from nine to seven types so the new daily WTC is called CAP7. As an assessment, CAP7 is compared to the original classification CAP9 and to the same WTs computed with the Twentieth Century Reanalysis (20CR and 20CRv2c). Over the reference period up to 90% of all the daily WTs can be correctly reproduced in the new WTC compared to the original series, with higher reliability in winter than in summer. In addition, the reliability of the classification is increasing from 1763 onward. The annual occurrence of each type reveals some trends, mostly a decrease in the number of cyclonic days and an increase of cyclonic days.

KEY WORDS weather types; synoptic climatology; reconstruction; instrumental data; Europe; atmospheric circulation

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1. Introduction

Weather type classifications (WTCs) are a simple tool to identify recurrent dynamical weather patterns over a specific region (Huth *et al.*, 2008a). They are useful to analyse variations in dynamical patterns through changes in their frequency of occurrence. Weather types (WTs) were first manually classified, and classifications were later automated based on detection algorithms, which is referred to as subjective and objective classifications (Philipp *et al.*, 2010).

For Europe, two subjective classifications have been widely used: the Hess and Brezowsky GrossWetterLagen (GWL) for Central Europe (Hess and Brezowsky, 1952, 1969; Gerstengarbe *et al.*, 1999) and the Lamb WTs for the British Isles (Lamb, 1972). These subjective classifications were then automated with the introduction of gridded mean sea level pressure series in the 1980s (e.g. Jenkinson and Collison, 1977; Jones *et al.*, 1993). With the use of classification algorithms, the number of available objective WTCs has increased in the last decades (Philipp *et al.*, 2010, 2014). The COST Action 733 'Harmonisation and Application of Weather Type Classifications for European Regions' project collected these WTCs and provided a platform to compare 17 objective and five subjective classifications for the European/North Atlantic domain (Philipp *et al.*, 2010). These classifications have been applied to numerical reanalysis (ERA-40 and ERA-Interim) providing daily WTCs over several decades. In addition, the NOAA-CIRES Twentieth Century Reanalysis (20CR) which reaches back to 1871 (Compo *et al.*, 2011) has been used by Jones *et al.* (2013) to reconstruct the Lamb WTs. However, because automated WTCs use gridded data, they are limited back in time to the availability of reanalysis outputs. On the other hand, longer time series of meteorological parameters have been homogenized recently for Europe, starting as far back as 1763 for few stations. Hence, the potential of extending the time series of WTs back in time does exist, but the available methodologies are not adequate for such an extension.

WTs provide important information on the state of the atmosphere and on its dynamics. They have been used to separate the influence of atmospheric circulation changes to climate trends (e.g. Bárdossy and Caspary, 1990). WTs can also be used to analyse the impact of a forcing (e.g. solar activity in Huth *et al.*, 2008b) on tropospheric weather through changes in the frequency of occurrence and persistence of daily WTs. In addition, WTs may

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serve as a powerful tool to investigate extreme events on a regional scale such as wind storms (e.g. Donat *et al.*, 2010). For instance, Wilby and Quinn (2013) used the Lamb WTs to reconstruct variations in fluvial flood risk. Climate models can be evaluated using WTs (e.g. Huth, 1997; Huth *et al.*, 2008a; Demuzere *et al.*, 2009; Pastor and Casado, 2012; Perez *et al.*, 2014). WTs have also been used for downscaling general circulation model outputs (Conway and Jones, 1998; Boé *et al.*, 2006). However, as mentioned in Wilby *et al.* (2004) these downscaling methods have weaknesses like intra-type variations in surface climate that are not well captured.

The occurrence of WTs has often been studied as an index of climatic variability (e.g. Lamb, 1965; Stefanicki *et al.*, 1998; Esteban *et al.*, 2006; Vrac *et al.*, 2014), including long-term trends in atmospheric circulation reconstructions (e.g. Lamb and Johnson, 1959; Rogers, 1984). For instance, Stefanicki *et al.* (1998) focused on changes in WTs frequency in the Alpine region since 1945. They found a shift towards less advective and more convective WTs, and an increase in the number of days with high pressure together with a reduction of northerly types. Esteban *et al.* (2006) developed a new WTC for Europe for the period 1960–2001. The trend analysis of their new types also reveals a reduction in the occurrence of northerly flows over Western Europe and more generally a decrease of meridional flows in summer. WTs have been used to analyse climate change in Europe: Bárdossy and Caspary (1990) used the Hess and Brezowsky classification over the 1881–1989 period and found an increase in the frequency of zonal types in December and January since 1973. This enhanced zonal flow in winter during the second part of the 20th century has also been pointed out in other studies (Slonosky *et al.*, 2000; Plaut and Simonnet, 2001; Kyselý and Huth, 2006). Furthermore, Kyselý and Huth (2006) also noticed an increase in the frequency of anticyclonic days from 1960 to 1990 and a decrease of cyclonic days in winter.

However, it has also been suggested that the Hess and Brezowsky GWL series contains some inhomogeneities. Especially, it shows a marked increase in the persistence of several types since the 1980s (Werner *et al.*, 2000; Kyselý and Domonkos, 2006; Kyselý and Huth, 2006). Cahynová and Huth (2009) analysed the persistence of circulation types in 23 classifications from 1957 to 2002, and did not find such a marked increase in any objective catalogues. Cahynová and Huth (2009) suggested that inhomogeneities in this manual time series could be responsible for this increase. Similarly, a reduction in the westerlies was found in the Lamb WTs, which was mostly resulting from the data and methods used (Jones and Kelly, 1982; Briffa *et al.*, 1990; Kelly *et al.*, 1997).

In this study, we propose and test a new automated methodology (Shortest Mahalanobis Distance, SMD), which allows us to produce a time series of daily WTs for Central Europe covering the last 250 years. This methodology combines long, homogenized, meteorological series for European stations and an existing WT series, based on the Cluster Analysis of Principal (CAP) Components

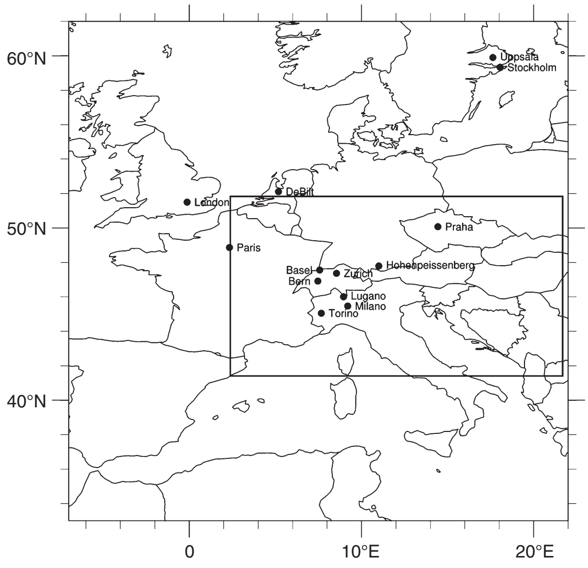

Figure 1. Stations locations and domain used by MeteoSwiss for computing CAP9 with ERA-40 and ERA-Interim.

classification. Basically, this combination allows us to calculate, at each station, the characteristic (average) value of each meteorological parameter for each WT. Conversely, for each day with observed parameters, we can deduce which WT best matches the measured meteorological parameters as long as meteorological data do exist. The CAP classification (e.g. Philipp *et al.*, 2010) serves here as reference. It is used by the Swiss Federal Office of Meteorology and Climatology (MeteoSwiss) to compute daily WTs over a large region in Europe centred over the Alps (Figure 1), including as an operational product based on the ECMWF IFS model forecast. MeteoSwiss keeps updating this WT series for different applications, especially those dealing with the special Alpine climate, and for verification of weather forecasts (Weusthoff, 2011). The CAP9 series has been computed back in time by MeteoSwiss based on the ERA reanalysis (ERA-40 and ERA-Interim) and starts in 1957. Here we reconstruct this classification further back in time using daily meteorological data starting in 1763. The final product is a daily time series of seven WTs (CAP7) extending from 1763 to 2009. We evaluate our methodology by using a score defined as the number of days for which the reconstructed WT is the same as in the series used for calibration. The probability of each day to be correctly classified is also computed. Further, we test the validity of our reconstruction (independently of the method) in two ways: (1) we calculate the WTs using reanalysis outputs (20CR and 20CRv2c) instead of instrumental series; and (2) we compare the first years of our reconstructed WT series with the long Hess and Brezowsky GWL series (to the extent that CAP and GWL WTs can be compared). We also briefly discuss long-term trends found in our reconstructed WT series.

The article is organized as follows. The data and the methods used to compute the new WTs are explained in Section 2. The results are presented and discussed in

Section 3 together with an analysis of the main changes in the occurrence of the WTs and an assessment of the new classification. We conclude this work in Section 4.

2. Methodology and data

Our methodology is based on an existing WT series, which we reconstruct back in time using instrumental series from few stations. The WT series that we use and reconstruct is based on the CAP classification, and more precisely on the CAP9 classification used by MeteoSwiss for a large European region covering the Alps and Central Europe (Figure 1). This classification is described in Section 2.1. We also use long and homogenized time series of meteorological measurements from several stations in Europe, which are described in Section 2.2. Our methodology is then to combine both data types, and this is described in Section 2.3.

2.1. Reference classification CAP9

The WTC reconstructed in this article is based on the CAP9 classification, issued from the CAP method. CAP is, alongside with GrossWetterTypes (GWT), a method used by MeteoSwiss to produce daily WTs. Both classifications are part of the 'cost733class' classification software (Philipp *et al.*, 2014; http://cost733.geo.uni-augsburg.de/cost733class-1.2), developed within the COST Action 733 (Philipp *et al.*, 2010). The ERA-40 (1 September 1957 to 31 July 2002) and ERA-Interim (1 August 2002 to 31 December 2010) reanalysis data (Uppala *et al.*, 2005; Dee *et al.*, 2011) are used by MeteoSwiss to calculate the WTCs. The CAP classification method consists of two steps. First, a principal component analysis is performed to derive the dominant patterns of variability (centroids), then a clustering procedure is applied to classify time series of the principal components. The classification is based on the daily mean sea level pressure field and is computed with 9, 18 and 27 types. The classification is computed over the Alpine region (3°–20°W, 41°–52°N, Figure 1).

The GWT method uses predefined types (strict zonal pattern, strict meridional pattern and cyclonic pattern) and calculates the correlation coefficients between each field in the input data set and the three types. The days are then classified depending on the three correlation coefficients and their combination. GWT are based on the sea level pressure or on the 500 hPa geopotential height, each with 10, 18 and 26 types. For more details on the methods and the classifications see Weusthoff (2011).

We selected the CAP9 WT series based on the ERA-40 reanalysis of the mean sea level pressure (computed by MeteoSwiss) over the period 1958–1998 (Table 1). Although several classifications are available, especially those studied by the COST Action 733, we only reconstruct the CAP9 classification in this study because Schiemann and Frei (2010) showed it to be the best predictor of surface climate conditions in the Alpine region, especially of precipitation. We also tested our method of reconstruction based on CAP18/CAP27 and on the GWT classification. It showed the best results when applied on CAP9. However, using few (nine) WTs clearly leads to a loss of information on the atmospheric flow, especially no type with a southerly flow exists in the CAP9 classification. Although it is a rare synoptic situation, it is a particular one for the Alps with potential strong precipitations on the south side and foehn wind on the north side.

Table 1. The nine WTs considered in the CAP9 classification used by MeteoSwiss.

Index	Full name
1	Northeast, indifferent
2	West-southwest, cyclonic, flat pressure
3	Westerly flow over Northern Europe
4	East, indifferent
5	High pressure over the Alps
6	North, cyclonic
7	West-southwest, cyclonic
8	High pressure over Central Europe
9	Westerly flow over Southern Europe, cyclonic

To reconstruct this CAP9 WT series back in time, we need long series of daily meteorological records in this region centred over the Alps in order to constrain the daily meteorological pattern or weather regime. In brief (Section 2.3), combining the CAP9 WT series available over the period 1958–1998 with any overlapping meteorological record allows us to calculate the average of each meteorological parameter separately for each of the WTs. These averages are called 'centroids'. The historical data are then used to calculate distances to these centroids for each day and each WT in the past. Intuitively, this reconstruction method works better with more records (more stations), and with stations spread over the region of interest in order to sample contrasted meteorological conditions defining the WT.

2.2. Instrumental data used to reconstruct WTs back in time

As the reference classification was computed for the Alpine region, all stations chosen are located in or close to the original domain used by MeteoSwiss (Figure 1). All the data and stations used are summarized in Table 2 and Figure 1. For the reconstruction, daily mean sea level pressure (p) and temperature (t) were chosen as they are available for most of the selected stations. The daily pressure tendency (Δp, the change with the previous day) was also used. As explained further on, another version of the classification was computed only with sea level pressure and pressure tendency data.

Since our method is calibrated over the period of CAP9 WT availability (1958–1998), the meteorological records must be homogeneous in time: any artificial long-term trend or spurious instrumental shift would bias the WT reconstruction. Hence, we use station data that have all been previously homogenized or checked for large errors in their series. We were also careful to select long time series with a very small number of missing values. Nevertheless, some series have few missing days (~3–5 days):

Table 2. Meteorological stations with daily records used for the reconstruction.

Stations	**Dates**	**Parameters**	**Reference(s)**
London	1763–1998	p, Δp	Cornes *et al.* (2012a)
Milano	1763–1998	t, p, Δp	Moberg *et al.* (2000)/Maugeri *et al.* (2002)
Uppsala	1763–1998	t, p, Δp	Moberg *et al.* (2000)
Stockholm	1763–1998	t, p, Δp	Moberg *et al.* (2000)
Torino	1763–1998	t	Di Napoli and Mercalli (2008)
Praha	1775–2009	t	Kyselý (2007)/Stepanek (2005)
Hohenpeissenberg	1813–2009	t, p, Δp	Winkler (2009)
DeBilt	1856–2009	p, Δp	Klein Tank *et al.* (2002)
Paris	1866–2009	t	Cornes *et al.* (2012b)
Bern	1866–2009	t, p, Δp	MeteoSwiss
Lugano	1866–2009	t, p, Δp	MeteoSwiss
Zürich	1999–2009	t, p, Δp	MeteoSwiss
Basel	1999–2009	t, p, Δp	MeteoSwiss

they were filled in with a 'K nearest neighbour' implementation method (e.g. Batista and Monard, 2002) which uses data from other stations to estimate the missing values. The Euclidean distance is computed between the series with missing data and the corresponding data available from other stations. The missing value is implemented by averaging the corresponding data of the K closest neighbour. The longest time series start in 1763 (London, Uppsala, Stockholm, Milan and Turin); those five stations with continuous records provide just sufficient information for the method to be applied. Although some stations have data available earlier, the records are often incomplete and their number is too low for the method to be applied. In order to better constrain the meteorological conditions over Europe and so the reconstructed WT, we added stations with records starting later than 1763 (Table 2). All stations have a complete time series from 1958 to 1998, which is our calibration period. Since some station records extend up to 2009, we calculated our WT reconstruction to 2009, adding two other stations, Zürich and Basel, specifically over the period 1998–2009. Eventually, these records allow us to produce a reconstruction of the CAP9 classification from 1763 to 2009. Increasing the number of stations does in theory increase the reliability of our reconstruction, but this has also drawbacks: a varying number of stations used over time may introduce some inhomogeneities in our reconstruction; the stations may be too distant and not record the same meteorological pattern (WT); and the risk of introducing uncorrected errors increases with the number of stations.

The use of temperature data for the reconstruction needs to be assessed as this might be an issue in terms of consistency with the original CAP9 classification. To address this issue, we computed a second classification using only sea level pressure and pressure tendency data (called CAP7NoTemp). WTs time series reconstructed with and without temperature data can hence be compared. Using temperature data raises three issues. First, all temperature data sets contain a positive trend linked to global warming. One could expect these trends to have an influence on the occurrence of the WTs. A second important point is to determine how temperatures affect the reconstruction in terms of consistency with the reference CAP9. The CAP WTCs of MeteoSwiss, used as reference, were computed only using sea level pressure from ERA-40/-Interim and not temperature. This impedes using the WTCs for partitioning a temperature trend into a circulation-driven and a thermodynamic component. A third potential unwanted impact may come from the warm bias that could be found in temperature records prior to 1870 (Böhm *et al.*, 2010).

To evaluate the method different combinations of stations were tested. As evaluation of these tests, we calculated the number of daily WTs correctly reconstructed by our method with respect to the reference WTs calculated from ERA-40 reanalysis, over the period 1958–1998 (Section 2.1). In many cases, adding a new data set did not increase significantly the quality of the final results, or even degrade it, or introduce an obvious inhomogeneity (a trend, for instance).

2.3. WTs reconstruction method, SMD

2.3.1. Step 1: calculating the average value of each meteorological parameter for each WT (centroids)

In a first step, all meteorological series (i.e. p, t, Δp, of all stations) are filtered by the daily WTs in order to calculate their average value for each WT (centroids) over the calibration period 1958–1998. If, and this is the principle of our methodology, these centroids are different enough to characterize each specific WT, then it should be possible to reconstruct uniquely the WTs from the meteorological series. This can be tested over the calibration period. Technically, in order to account for the seasonal cycle of the meteorological parameters, each centroid is separately calculated for each calendar month. An exception are the summer months: some WTs are so rare in summer that their monthly average values are not reliable (or inexistent); for this reason the centroids were calculated over the whole summer season (June-July-August) instead of the individual months. Note that computing the summer months together could have an influence on the centroids and therefore on the JJA WTs. It was shown that the atmospheric circulation pattern tends to differ in June compared to July and August (e.g. Folland *et al.*, 2009). The centroids of the mean sea level pressure are shown in Figure 2, for clarity only their seasonal mean values are shown. Note that only seven WTs (and seven centroids) are presented in Figure 2 because the original nine-WTs classification of CAP9 has been simplified here to seven WTs (CAP7), as detailed in Section 3.1. The differences between the centroids are larger in winter than in summer (for p and Δp). Therefore, we expect the reconstruction of WTs to be more reliable for winter than for summer months. This seasonal difference may be related to the fact that meteorological patterns, or 'centres of action', in Europe are not as well defined in summer as in winter. The polar front being located more south during winter months, the circulation of low pressure systems is on average lower in latitude across Europe and have a lower pressure minimum (i.e. enhanced pressure gradients). Therefore, the contrast between low and high pressure centres is stronger during winter months. The smoother summer sea level pressure field leads to some difficulties in the application of the method, because the differences between the centroids are not as pronounced as in winter.

2.3.2. *Step 2: inferring WTs by measuring the distance to the centroids*

We assume that the characteristic pattern of each WT, quantified by its centroids, has been the same in the past: for each day, the meteorological parameters (p, t, Δp) are compared with the different centroids, and we select the WT whose centroids are closest to these meteorological parameters. In more detail, let x_j be a vector with all meteorological parameters available for the day j, from stations 1 to n:

$$x_j = \left\{ t_1, p_1, \Delta p_1, t_2, p_2, \Delta p_2, \ \dots \ , t_n, p_n, \Delta p_n \right\} \quad (1)$$

Note that all three meteorological parameters are not necessarily available for all stations. Further, let i denote the WT index (1–9, or 1–7, see Section 3.1). The average values (centroids) μ_i have been computed for the x_i over the calibration period (Figure 2). Then, for each day j for which meteorological parameters are available, the Mahalanobis distance D is calculated for each WT i as:

$$D_j^2 (i) = \left(x_j - \mu_i \right)^T S_i^{-1} \left(x_j - \mu_i \right) \quad (2)$$

in which S_i is the covariance matrix of the meteorological parameters between all stations for the WT i; and T stands for the transpose of the vector $(x_j - \mu_i)$. In contrast to the Eucledian distance, the Mahalanobis distance also accounts for the covariance between the station series. For each day j, the WT i that minimizes the Mahalanobis distance D is considered as the most probable and is attributed to this day. This method is applied to each day from 1763 to 2009, providing daily WTs over this period.

2.3.3. *Step 3: testing the reconstructed WTs*

The ability of our method to reconstruct WTs depends on their discrimination by the centroids, that is, whether each WT has a meteorological pattern different enough from other patterns. This ability obviously depends on the chosen WT classification, including the classification type and the WT number, as well as on the availability of meteorological parameters.

An obvious quantification of our method performance is the number of days that have been correctly classified over the calibration period 1958–1998 ('matching days'), that is, with the same WT as in the reference series (used to calculate the centroids). If the method worked perfectly, this score would be 100%. The performance will be discussed in details in Section 3.

In addition, for each day, we calculate the probability P_i of each different WT$_i$, based on the distance D_i, as:

$$P(i) = \frac{\exp\left(-\frac{1}{2} D_i^2\right) \times F_i}{\sum_{i=1}^{7} \exp\left(-\frac{1}{2} D_i^2\right) \times F_i} \quad (3)$$

in which D_i is the Mahalanobis distance, and F_i the frequency of the WT i (over the calibration period). This formula is based on the assumption that the squared distance D^2 is actually a probability density, and that F_i quantifies the average proportion of each WT in the total decomposition of the probability density D^2. For each day, the value of the highest probability P_i gives us some idea on how well our method performs this particular day, given the meteorological conditions, the chosen WTC, the centroids, etc. However, both metrics (score and P_i) test the performance of our method for a given WT classification, CAP9 here. There is no obvious technique to independently test our method. Hence, several comparisons have been tested, reviewed in the next section, by comparing the reconstructed WTs to other series of WTs. We calculated a CAP7 WT series by using the 20CR (and 20CRv2c) reanalysis outputs instead of the meteorological series, using grid points within the domain shown in Figure 1. It is important to note that the same centroids (computed from ERA-40/-Interim) have been used as in the WTs from MeteoSwiss in order to have the same WTs. Since the CAP classifications are computed with absolute sea level pressure values, biases may affect the results. The mean sea level pressure over the Alps tends to be higher in 20CR reanalysis than in ERA reanalysis. This leads to an overestimation of the number of anticyclonic days and easterly flows and an underestimation of the number of westerly situations. This affects the mean frequency of occurrence of the WTs but not the annual/decadal variability, which is similar in 20CR and ERA. As the resolution of 20CR (2° × 2°) is coarser than ERA (1° × 1°), the domain used is slightly smaller (4°–20°W, 42°–52°N instead 3°–20°W, 41°–52°N). 20CR has 56 members, but in the following only WTs computed from the Ensemble mean of these members are shown. As it can be expected, 20CR and 20CRv2c have a similar WTs frequency of occurrence. Although 20CRv2c goes back to 1851 some precautions need to be taken concerning the first years of the data set. Marine pressure data used for the reanalysis have a bias from 1851 to about 1865 and therefore affect the average

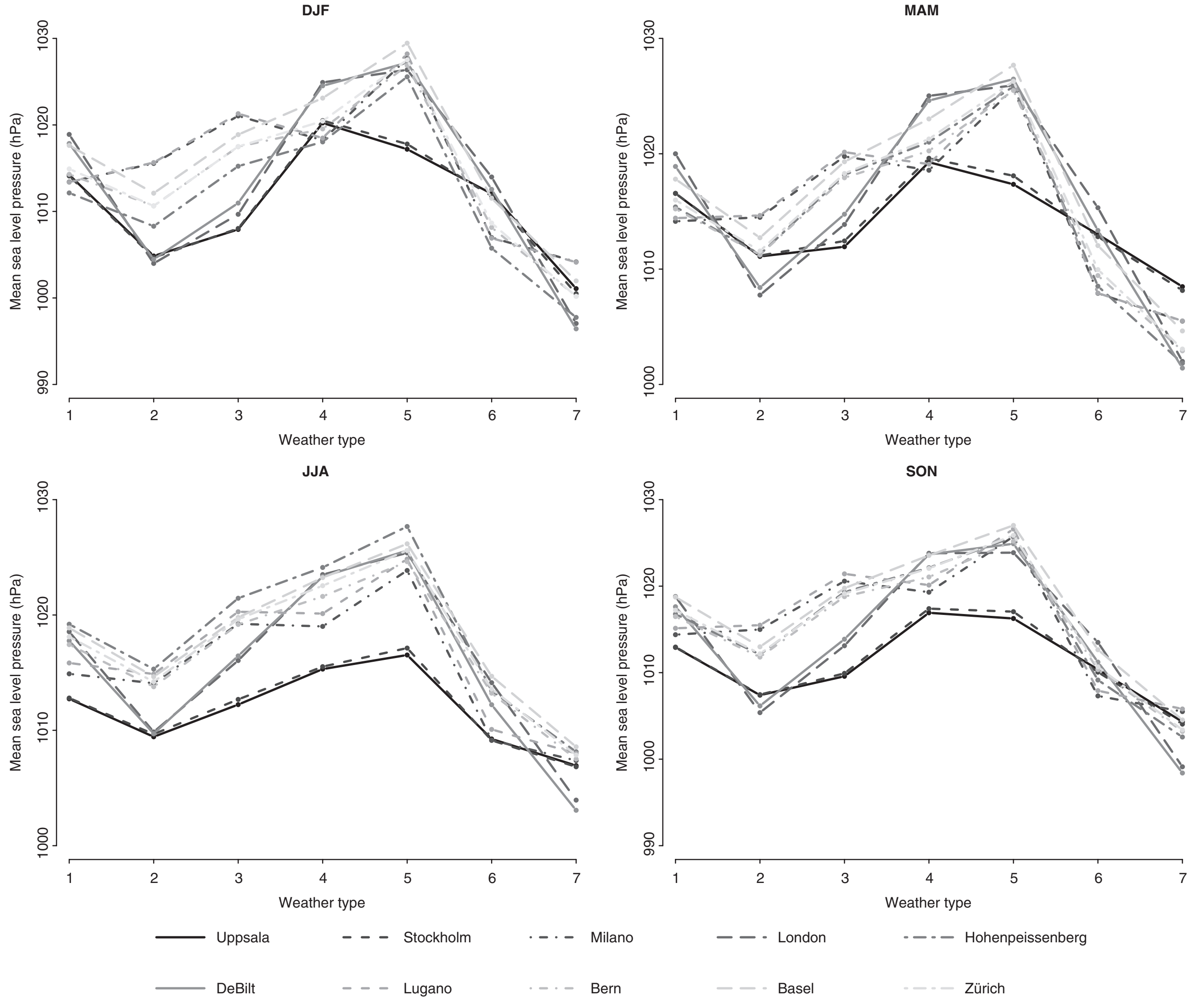

Figure 2. Seasonal mean sea level pressure centroids of all CAP7 types. Each curve corresponds to a station. The centroids are computed for the calibration period 1958–1998.

mean sea level pressure in the data set (Woodruff *et al.*, 2005; Wallbrink *et al.*, 2009).

There is no identical WTC available prior to 1851, however Kington (1988) provides a series of daily GWL from 1781 to 1786. The GWL types also cover Europe (with a larger domain that is more centred to the north), so although it is another classification we can still compare the frequency of occurrence of similar patterns in both classifications over these 5 years.

3. Results and discussion

3.1. Calculation and evaluation of the new time series of CAP7 WTs

We performed preliminary evaluations by applying the SMD method with different classifications, GWT and CAP, and with different numbers of types. The results showed that the method performs best, in terms of matching days, when applied with the CAP9 classification. With the GWT classification, less than half of the days over the calibration period can be correctly classified (score < 50%), whereas the score is higher than 75% with CAP9 (Table 3). These differences in the quality of the results probably come from the fact that the GWT centroids that we calculate with the instrumental data are much closer to each other than they are when using the CAP9 classification. They do not discriminate well the synoptic patterns, resulting in WTs that are more difficult to define and in a higher percentage of days that are misclassified (relative to the original classification).

The problem arose that the WTs 8 and 9 of the CAP9 classification are almost inexistent in summer (June, July and August) over the period 1958–1998. They only appear a few days; and so there are not enough values to calculate representative centroids. To prevent a reduction in the reliability of the results (in particular for summer months), the classification CAP9 was reduced to 7 types (CAP7). This reduction was done by merging four types of CAP9 (Tables 1 and 4): type 5 (‘High pressure over the Alps’) with type 8 (‘High pressure over Central Europe’)

Table 3. Stations used to reconstruct the CAP7 WTs and percentage of matching days ('score') over the reference period (1958–1998) for the whole year (ANN), December/January/February (DJF-winter), March/April/May (MAM-spring), June/July/August (JJA-summer) and September/October/November (SON-autumn). The last column is the period of our final WT series for which these stations have been used.

Stations	ANN	DJF	MAM	JJA	SON	Corresponding period of the final WT series
Five stations (Lo, Mi, Up, St, To)	76.3	79.9	75.7	70.7	78.9	1763–1774
Six stations (Lo, Mi, Up, St, To, Pr)	77.5	81.2	77.4	72.2	79.2	1775–1812
Seven stations (Lo, Mi, Up, St, To, Pr, Ho)	83.5	86.7	83.6	78.3	85.5	1813–1855
Eight stations (Lo, Mi, Up, St, To, Pr, Ho, De)	83.9	86.4	84.1	79.3	85.9	1856–1865
Ten stations (Lo, Mi, Up, St, To, Pr, Ho, De, Be, Lu)	86.3	90.1	86.0	80.3	88.8	1866–1874
11 stations (Lo, Mi, Up, St, To, Pr, Ho, De, Pa, Be, Lu)	86.9	90.8	86.5	81.1	89.1	1875–1998
Nine stations (St, Pr, Ho, De, Pa, Be, Lu, Zu, Ba)	86.6	89.3	88.1	81.8	87.2	1999–2009

into the new type 5 ('High pressure over Europe'), and type 7 ('West-southwest, cyclonic') with type 9 ('Westerly flow over Southern Europe, cyclonic') into the new type 7 ('Westerly flow over Southern Europe, cyclonic'). These names of the new types 5 and 7 correspond to the direction of atmospheric flow over our region of interest (Figure 1). These two couples of types have been chosen because they have a similar sea level pressure pattern over Central Europe, and thus their merging does not affect the relevance of the classification. The other WTs are the same in CAP9 and CAP7 (Table 4).

Note that, because types 8 and 9 of the CAP9 classification are more frequent during winters, it would be technically possible to reconstruct nine types only for the winter months, but this would make our WT reconstruction inconsistent, with different types during the year, and so we decided to apply this reduction to the whole year.

To illustrate the atmospheric flow typical of each WT, the average fields of sea level pressure and 850 hPa temperature anomalies (relative to the long-term mean) were calculated for each WT with the ERA40 reanalysis, over the calibration period 1958–1998. These so-called composites are displayed in Figure 3. As already explained, these patterns are more clearly defined in winter. The WTs can be divided into three categories. Types 1 (NE), 4 (E) and 6 (N) have mostly a continental flow with cold air coming from the east or the north. Types 2 (WSW), 3 (W) and 7 (WC) have a southwesterly to northwesterly flow with warm anomalies for 2 (WSW) and 3 (W) and cold anomalies for 7 (WC). Type 7 (WC) is the most cyclonic of all the types with a low pressure system located south of the North Sea. Finally, Type 5 (HP) is anticyclonic with temperature anomalies that are more dependent on the season, warmer in winter and at the boundary between warm and cold anomalies for the others seasons.

A straightforward evaluation of our methodology is to compare our reconstructed WT series over the reference period 1958–1998 with the original WT series calculated from ERA-40 reanalysis and used to calculate the WT centroids (Figure 2). If the available data could perfectly constrain the atmospheric flow pattern, our method would be able to correctly infer the same daily WT as in the reference series. We calculate the number of days over the 1958–1998 period for which the inferred WT is the same as in the reference series: this number of matching days is the calibration score of our methodology, shown in Table 3. Depending on the season, between 75 and 90% of all daily WTs over the period 1958–1998 can be correctly reproduced. This score is higher in winter and lower in summer. In addition, the score also depends on the WTs, some of them are better reconstructed than others (Table 5). Since the proportion of WTs varies in time, the score calculated over the 1958–1998 period do not exactly apply to other periods of time.

As expected, using more meteorological series increases the score (number of matching days) over the 1958–1998 period, by about 10% at most. To maximize the reliability of our new CAP7 WT series, we have used all the records shown in Table 2, over their respective period of time. Hence, our WT series is a merging of several WT series calculated over different periods of time, indicated in the last column of Table 3. We computed the percentage of matching days over the same reference period for each combination of available predictors. Adding meteorological series over time increases the reliability of our WT reconstruction, but it also introduces inhomogeneities in our reconstructed WT series: the comparison of annual WT occurrence (Section 3.2) shows that for the first years and for summer the new classification is less reliable. Starting from 1813 the reliability increases notably. Even though the method works with only five stations, some differences appear between the 1763–1813 period and the rest of the time series.

We can estimate the reliability of our reconstructed WTs at the daily time scale, with the probabilities of the WTs. For each day, Equation (3) allows us to calculate the probabilities $P(i)$ of each of the seven WTs, based on their Mahalanobis distance to the observed meteorological parameters. The 'closest', most probable, WT is selected for each day. This selection is more reliable when the maximum probability is higher: a high probability means that the meteorological parameters available for this day do strongly discriminate the seven WTs of CAP7, with a limited risk of a wrong classification. Conversely, a low maximum probability, or a maximum probability not so different from the second highest, means that the discrimination between the seven WTs is not so strong, with an elevated risk of wrong classification for this day. The average values

Table 4. CAP7 classification used in this work, based on CAP9 described in Weusthoff (2011).

Index	Abbreviation	Full name	Corresponding CAP9 WTs
1	NE	Northeast, indifferent	1
2	WSW	West-southwest, cyclonic, flat pressure	2
3	W	Westerly flow over Northern Europe	3
4	E	East, indifferent	4
5	HP	High pressure over Europe	5 + 8
6	N	North, cyclonic	6
7	WC	Westerly flow over Southern Europe, cyclonic	7 + 9

Table 5. Correlation coefficients between our reconstructed CAP7 WT series and (1) the CAP7 WT series calculated with ERA-40 (over 1958–2009), (2) the CAP7 WT series calculated with 20CR (1871–2009).

WT index	ANN		DJF		MAM		JJA		SON	
	ERA	20CR	ERA	20CR	ERA	20CR	ERA	20CR	ERA	20CR
1	0.71	0.36	0.91	0.56	0.76	0.33	0.81	0.45	0.79	0.62
2	0.82	0.61	0.91	0.46	0.84	0.47	0.85	0.55	0.88	0.83
3	0.75	0.49	0.94	0.66	0.70	0.52	0.74	0.42	0.89	0.65
4	0.83	0.63	0.82	0.64	0.80	0.51	0.87	0.65	0.92	0.74
5	0.96	0.88	0.98	0.92	0.96	0.71	–	–	0.94	0.90
6	0.72	0.50	0.91	0.77	0.91	0.65	0.70	0.54	0.73	0.66
7	0.94	0.82	0.96	0.86	0.98	0.87	0.85	0.69	0.95	0.77
Mean	0.82	0.61	0.92	0.70	0.85	0.58	0.80	0.55	0.87	0.74

of the maximum probability (probability of the selected WT) is shown in Figure 4. A 365-day running mean is applied to the curve to smooth out seasonal variations. There is an overall increase in this maximum probability over the years. The values are particularly lower during the period 1763–1812 with probabilities between 75 and 80%, a period with the fewest number of meteorological records (Table 3). In 1813, the probability increases notably to values between 80 and 85%. The values are then mostly above 85% from 1865 onward, consistently with the increase in the number of available records (Table 3). The probabilities are highest (almost 90%) between 1958 and 1998. It corresponds to the reference period during which the centroids were calculated, so it is not surprising that the centroids optimally discriminate the days on this period. Hence, these variations in the probability of the chosen daily WTs show that the first 50 years of our reconstructed WTs series are the less reliable; it is important to take this into account when considering the series. The probabilities for CAP7NoTemp follow the same trends and variability as CAP7 but the curve is systematically lower by 2–5%. These lower probabilities as well as lower matching days scores (not shown) help us to quantify the contribution of the temperature records in the reconstruction in terms of similarity with the reference.

3.2. WTs annual occurrence

Figure 5 shows the annual occurrence of the reconstructed CAP7 WTs in green with a 10-year running mean in black and the CAP7NoTemp in dashed black. We analyse the evolution of the occurrence of each WT and compare this (at the decadal time scale) with the reference classification (based on ERA reanalysis, see Section 2.1) in blue and the types computed from the Ensemble mean of the 20CR (20CRv2c) reanalysis in red (dashed red).

At this decadal time scale, the occurrences of our reconstructed WTs match quite well the reference series of CAP7 based on ERA, both in terms of absolute level and in terms of trends. Exceptions are a lower occurrence of type 3 (W) and higher occurrences of types 6 (N) and 7 (WC) in our reconstructed series compared to the ERA-based series. It is clear that the occurrences based on the 20CR reanalysis data have systematic shifts compared with the other series, with an overestimation of the number of anticyclonic days, but present very similar decadal changes. Hence it is difficult to use the series based on 20CR to discuss the absolute values of WT occurrence. Also a possible pressure bias in 20CRv2c from 1851 to 1865 (Woodruff *et al.*, 2005; Wallbrink *et al.*, 2009) limits the comparison to an analysis of the correlation and changes in the decadal variability.

We focus here on the low frequency variability of the annual occurrence (Figure 5). Four of the seven types show a trend (significant at the 5% level) over the whole time series (1763–2009). The trend is positive for types 1 (NE) and 5 (HP) and negative for types 2 (WSW) and 7 (WC). Types 3 (W) and 4 (E) do not have any significant trends over the whole 247 years but both show a positive trend over the 1871–2009 period. Finally, type 6 (N) has also a significant negative trend after 1871. Note that a similar trend in the frequency of northerly types was found by Stefanicki *et al.* (1998) and by Esteban *et al.* (2006).

The strongest decadal trends are found in types 5 (HP, positive) and 7 (WC, negative). The occurrence of anticyclonic days of type 5 (HP) increases after 1870 and this trend is strongest between 1960 and 1990. These latter

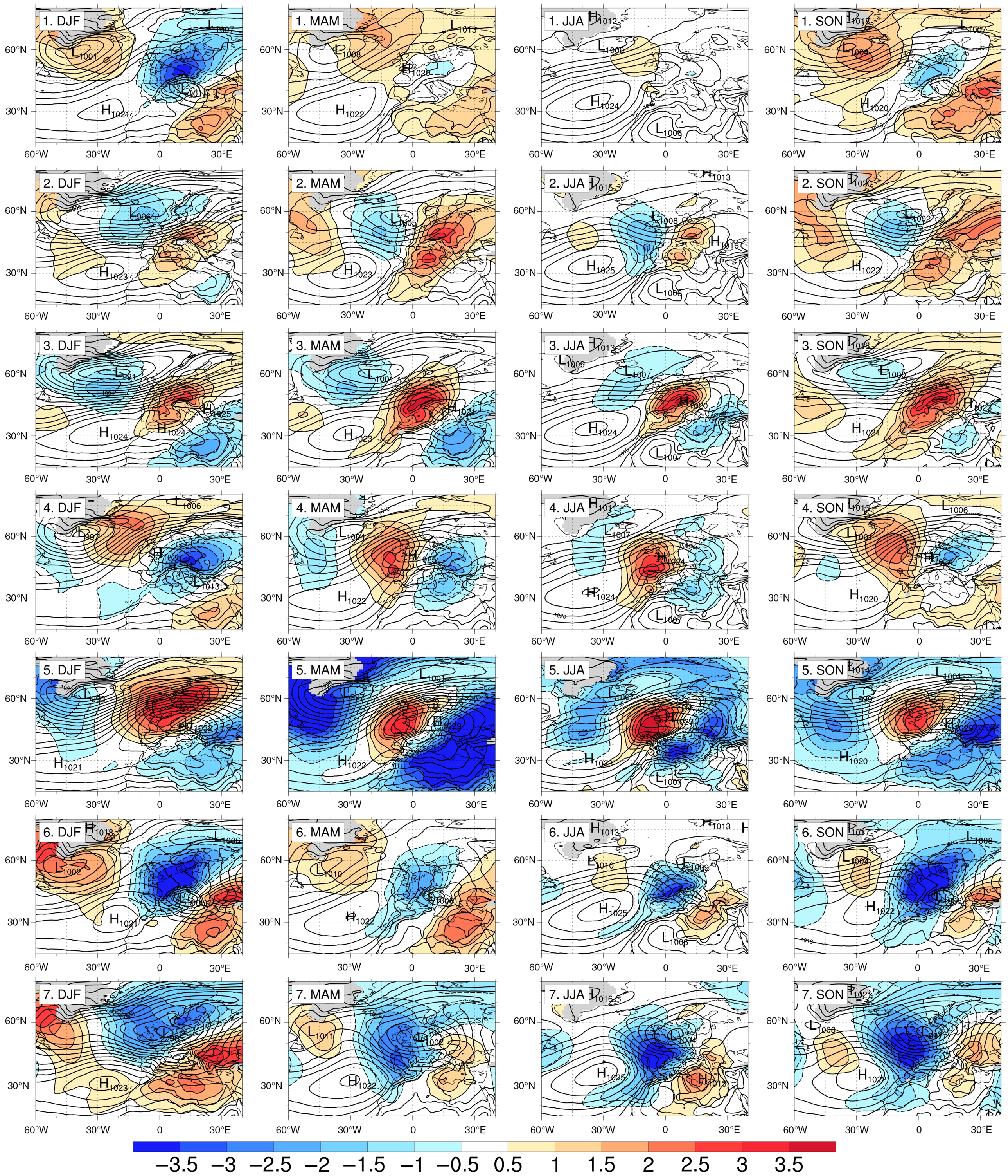

Figure 3. CAP7 composites computed from 1958 to 1998 with ERA-40. Empty contours show the mean sea level pressure in hPa and filled contours the temperatures anomaly in Celsius relative to the 1958–1998 mean (negative values contours are dashed).

trends have mostly occurred during winters, as shown by Figure 6, which presents the seasonal occurrences of WTs. This strong positive trend from 1960 to 1990 in the winter occurrence of anticyclonic types was also found by Kyselý and Huth (2006) using the Hess–Brezowsky classification and by Stefanicki *et al.* (1998) using the Schüepp's classification. This trend does not extend over a longer period as there is even a negative trend from 1880 to 1960. The pattern is reversed for type 7 (WC). The occurrence of a cyclonic flow clearly decreases after around 1870. Their seasonal variations show various features. In winter, the trend becomes negative at the end of the 20th century, as also found by Kyselý and Huth (2006) for the cyclonic types. Type 7 (WC) is in fact the most cyclonic type over

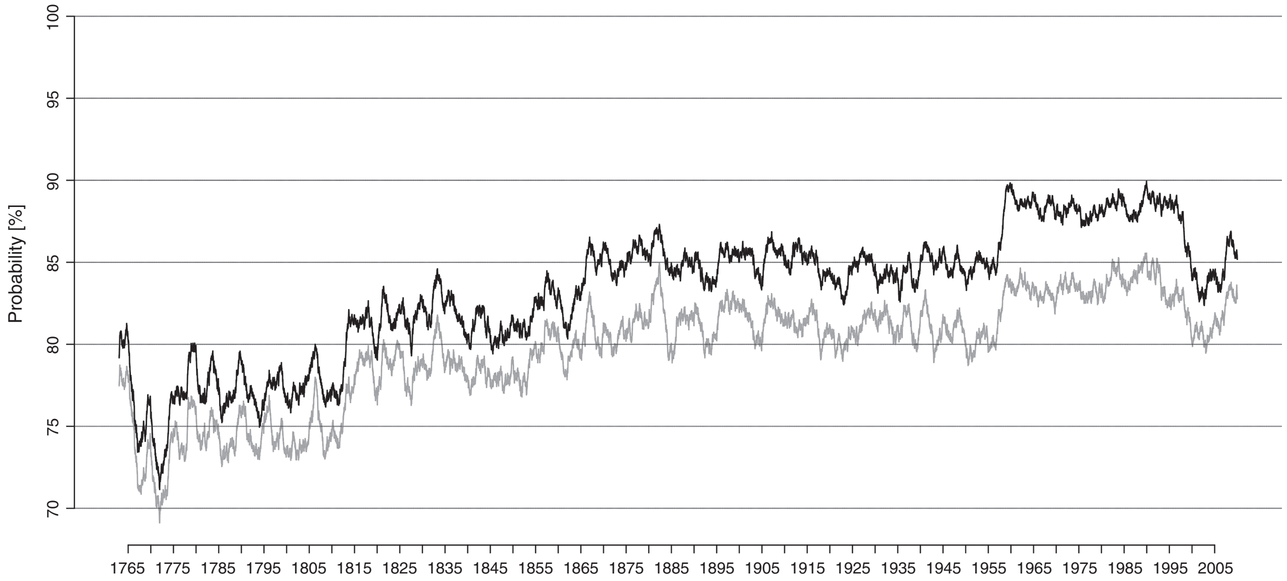

Figure 4. A 730-day running mean of the daily maximum probability (in %) of the new CAP7 (black) and CAP7NoTemp (grey) WT series.

Europe in the new classification. In summer, we also see a negative trend. For spring and fall, there is first a positive trend until around 1870 followed by a negative trend.

An additional characteristic of WTs, independent of their annual or seasonal occurrence, is their mean persistence (i.e. how many days the same WT lasts on average). Type 5 (HP) lasts on average 2.67 days between 1763 and 1799. This value increases over time and reaches 3.52 days in 1950–2009. This is the most persistent type, and also the one with the most important variations, with an increase of the mean persistence over time. There is a small decrease in persistence in type 7 (WC). The maximum mean persistence is 2.6 days in the period 1800–1849 it then decreases to 2.42 days in 1950–2009. All the other types have only insignificant variations in their persistence and a shorter lifetime with values between 1.6 and 1.8 days.

The CAP7NoTemp appears to be similar to CAP7 in terms of annual frequencies of occurrence. Over the whole period of the reconstruction the decadal variability is almost identical. However, types 3 (W), 4 (E), 5 (HP) and 7 (WC) have shifted means in the early decades from 1760 to the 1820s. We expect CAP7 to be a better reconstruction of WTs occurrence than CAP7NoTemp. However, the matching scores are all computed over the reference periods and they do not provide any information of a potential bias resulting from the use of temperature data in the early years.

As explained in Section 2.3, our WT reconstruction is less reliable for summers in general (the red curves in Figure 6), because the centroids are less contrasted. However, some interesting features are noticeable in Figure 6. We notice a higher occurrence of type 5 (HP) over the period 1763–1813, even more remarkable for CAP7NoTemp. This compares well with the higher occurrence of anticyclonic days in summer around 1800 found by Brönnimann (2015) in the WT series produced by Auchmann *et al.* (2012), a series which was created to analyse 'the year without a summer' 1816. Also, the occurrence of type 4 (E) is both higher and more variable before approximately 1875, possibly indicating a positive bias. For type 6 (N) as well as for type 1 (NE), there could be an underestimation of the number of days during the first decades in summer; the annual occurrence values are lower with a sudden rapid increase around 1810. This also enhances the positive trend of these two types.

In the seasonal and annual occurrences, the decadal variabilities of CAP7 and CAP7NoTemp are always identical but a shift in the mean is sometimes visible over the whole 247 years. These shifts are not limited to only one season but concern all of them. In addition, they exist over concern the whole period of the reconstruction. Hence, it is unlikely that the potential summer temperature bias prior to 1870 (Böhm *et al.*, 2010) is the cause of these differences.

3.3. Comparison with other time series

To extend the comparison over a longer period, we use the WTs computed with the 20CR and 20CRv2c reanalysis data back to 1871. Note that most of stations used for our reconstructions were also assimilated into the 20CR reanalysis. As already mentioned, the 20CR-based annual occurrence seems to be biased (overestimation of anticyclonic and easterly days), with some large differences compared to the ERA-based occurrence in the climatology of a few types. In addition, 20CRv2c is known to be biased from 1851 to 1865, so we do not compare it with our reconstruction over this period (Woodruff *et al.*, 2005; Wallbrink *et al.*, 2009). Still, the 20CR-based series provides a valuable comparison over more than a century, at least in terms of correlation (Figure 5). We observe a systematic shift in the mean between our reconstruction (black) and the one based on 20CR (red). The number of days classified as (south-) westerly or northerly flow (2, 6 and 7) is lower in 20CR. For types 4 (E) and 5 (HP) the situation is reversed. We will not focus here on these differences which result

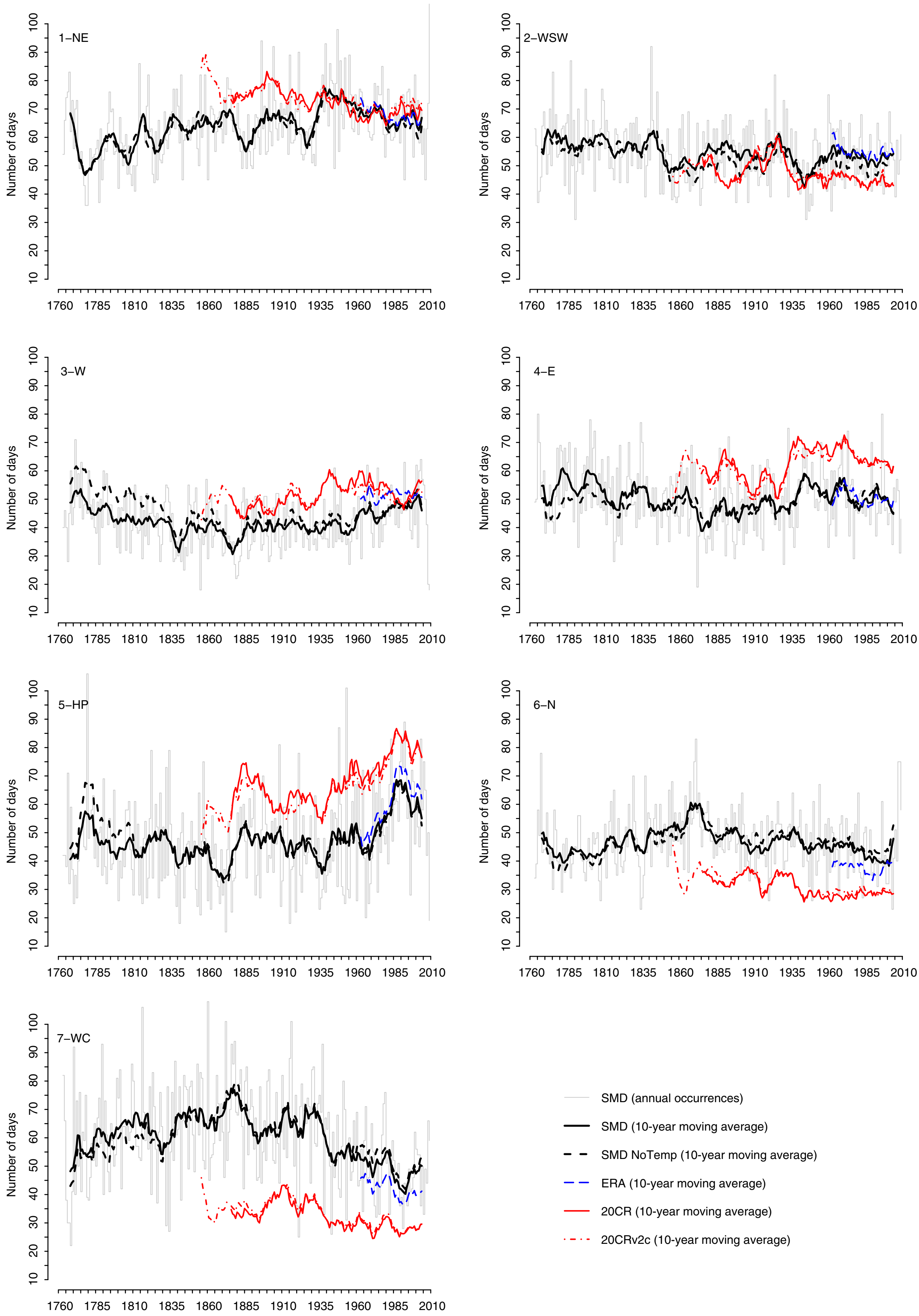

Figure 5. Annual occurrence of the reconstructed CAP7 WTs (green) from 1763 to 2009 with its 10-year running mean and CAP7NoTemp 10-year running mean. The 10-year running means of the CAP7 series reconstructed from ERA, 20CR and 20CRv2c reanalysis are also shown.

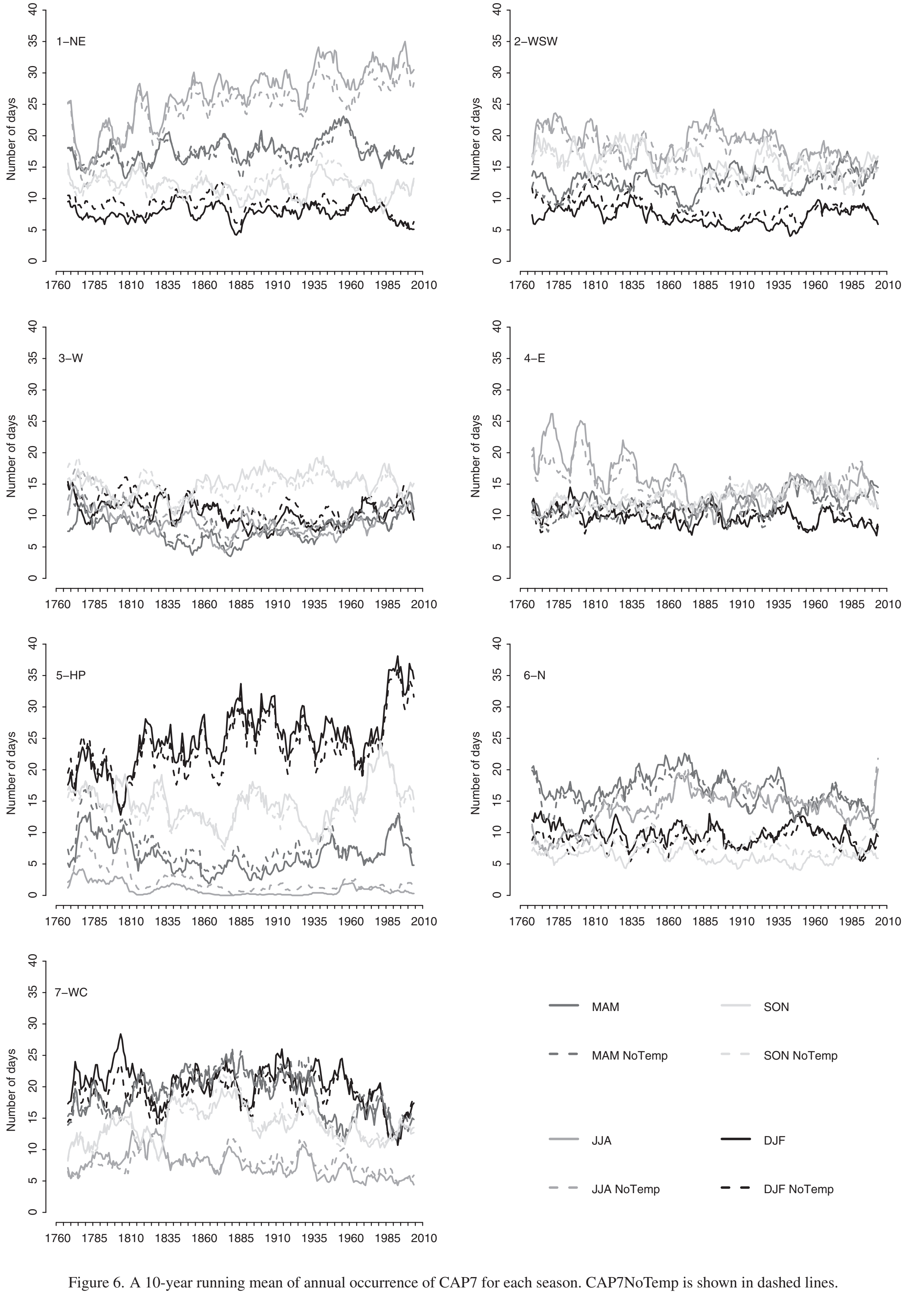

Figure 6. A 10-year running mean of annual occurrence of CAP7 for each season. CAP7NoTemp is shown in dashed lines.

from the computation of the 20CR types but only on the correlation and trends. The mean correlation coefficient between the new classification and 20CR is 0.62 (Table 5). This value differs largely between the types. Type 5 has the highest value ($r = 0.88$) with an identical decadal variability and also a positive trend. For type 1 the correlation is only 0.36. Again, the values are the highest in winter and the lowest in summer. The temporal pattern in type 1 (NE) is particular, with a good correlation and also the same mean from 1935 to 2008. However, prior to 1935 we observe a shift between the two classifications (Figure 5); type 1 (NE) is the only type with such a large change in the difference between the two curves. In addition, all types except type 1 show trends similar to those derived from 20CR from 1871 onward, even if the correlations are relatively low. For type 1, the trend in the 20CR-based series is clearly negative, whereas the trend in the new classification is positive. Types 3 (W), 4 (E) and 6 (N) do not display any trend over the 245 years, but they have either a positive (3 and 4) or a negative (6) trend from 1871 onward.

Prior to 1870, a direct comparison with another WT series is not possible. However, we used a time series of the Hess and Brezowsky GWL available from 1781 to 1786 as comparison (Kington, 1988). The comparison between CAP7 and GWL of the occurrence of their WTs between 1781 and 1786 reveals several similarities (not shown). Days classified as type 2 (WSW) or 3 (W) in CAP7 are also predominantly classified as westerly by GWL. For days identified as type 7 (WC), they are classified as westerly or cyclonic over Europe. Easterly types 1 (NE) and 4 (E) mostly correspond to anticyclonic types (with easterly flow over the Alpine region) and easterly types in GWL. The pattern is also similar for type 5 (HP) with days also categorized as anticyclonic in GWL. Only days classified as type 6 (N) in CAP7 are not showing any specific pattern in GWL with approximately the same number of days identified as east, north, west or anticyclonic types.

4. Conclusions

The CAP9 daily classification used by MeteoSwiss (Weusthoff, 2011) was extended back in time with a new method (SMD) based on few meteorological records. We selected European weather stations with daily records from 1763 to 2009, records which had been homogenized by previous studies. The CAP9 classification (computed with ERA-40/-Interim reanalysis data) was used as a reference from 1958 to 1998, but it was reduced from 9 to 7 types. The SMD method of reconstruction was tested with other WT classifications (e.g. GWT) but the results were only consistent for CAP9, which was chosen for calibration. Our reconstructed WT time series is highly correlated with the original MeteoSwiss classification used for calibration. The highest correlations are found for winter and the lowest for summer. The method performs better for winter months as the types are easier to discriminate from each other. To extend the assessment of our reconstructed series back in time, we used the same WTC computed with 20CR and 20CRv2c data. Owing to differences in the original computation (relative to ERA-based series), the time series is biased. However, this bias does not affect the correlation and allows a comparison from 1871 to 2009 with the highest correlation found for the anticyclonic type. A comparison with GWL from 1781 to 1786 also shows similar frequencies although a direct comparison between both classifications is not possible, due to the different number of types and different spatial domains of computation.

The analysis of the annual count reveals a bias in the new WTC from 1763 to 1813 especially for summer (JJA). It is important to be aware of these potential misclassifications when using the daily time series. The reconstruction of daily types is accompanied by the value of their probability to be correctly classified. This is an important information on the reliability of the WTs; and it can be used to, for instance, exclude days considered as too uncertain.

A second version of the reconstructed WTs series was computed using only pressure and pressure tendency data to be fully consistent with the reference CAP classification. It provides a time series independent from temperature data. However, this series matches less well the reference CAP WT series than the one also based on temperature data, which justifies assimilating temperature data in addition to pressure data.

There are several trends, which were identified in the annual occurrence time series. On the low, decadal, frequency two types have a strong opposite trend; there is an increase in the number of anticyclonic days with the quickest increase in winter (DJF) from 1960 to 1990, and a decrease in the number of cyclonic days, especially after 1870. These trends as well as other changes in the decadal variability were confirmed by other studies; the increase in the number of anticyclonic days was also found by Stefanicki *et al.* (1998) and Kyselý and Huth (2006). The slow decrease in the frequency of occurrence of northerly flows after 1870 was also pointed out by Esteban *et al.* (2006) and Stefanicki *et al.* (1998). The decrease in the number of cyclonic days found by Kyselý and Huth (2006) is also apparent in CAP7 with the negative trend in 'westerly flow over Southern Europe' which is the most cyclonic type.

This new 247-year long time series of daily objective WTs is a useful tool for analysing low (centennial) and high (daily) frequency changes in the occurrence of weather patterns over Europe. The limitations come from the small number of types, which do not allow a detailed synoptic analysis. In addition, caution should be taken when the classification is used for summer months in the period 1763–1813.

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